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Modelling self-pollution of globular clusters from AGB stars

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ABSTRACT
A self-consistent model of the chemical evolution of the globular cluster NGC 6752 is presented to test a popular theory that observed abundance anomalies are due to "internal pollution" from intermediate mass asymptotic giant branch stars. We simulated the chemical evolution of the intracluster medium under the assumption that the products of Type II SNe are completely expelled from the globular cluster, whereas the material ejected from stars with $m \lesssim 7$ M$_\odot$ is retained, due to their weak stellar winds. By tracing the chemical evolution of the intracluster gas we have tested an internal pollution scenario, in which the Na- and Al-enhanced ejecta from intermediate mass stars is either accreted onto the surfaces of other stars, or goes toward forming new stars. The observed spread in Na and Al was reproduced, but not the O-Na and Mg-Al anticorrelations. In particular, neither O nor Mg are sufficiently depleted to account for the observations. We predict that the Mg content of Na-rich cluster stars should be overwhelmingly dominated by the ^{25,26}Mg isotopes, whereas the latest data shows only a mild ^{26}Mg enhancement and no correlation with ^{25}Mg. Furthermore, stars bearing the imprint of intermediate mass stellar ejecta are predicted to be strongly enhanced in both C and N, in conflict with the empirical data. We show that the NGC 6752 data are not matched by a model incorporating detailed nucleosynthetic yields from asymptotic giant branch stars. Although these stars do show the hot Hydrogen burning that seems required to explain the observations, this is accompanied by Helium burning, producing primary C, N, Mg and Na (via HBB) which do not match the observations. Based on current theories of intermediate mass stellar nucleosynthesis, we conclude that these stars are not responsible for the most of the observed globular cluster abundance anomalies.

Key words: Galaxy: globular clusters: NGC 6752 – stars: abundances – stars: chemically peculiar – stars: AGB – nucleosynthesis

1 INTRODUCTION

Most Galactic globular clusters (GCs) consist of stars that share the same characteristic Fe abundance and are consequently considered monometallic. However, recent studies have found broad variations in the abundance of some lighter metals. There is a growing list of globular clusters known to have CNO inhomogeneities and O-Na and Mg-Al anticorrelations in stars at different stages of evolution, from the red giant branch to the main-sequence. These abundance anomalies are not seen in field stars at the same metallicity – they are peculiar to the cluster environment. The two main competing hypotheses to explain the curious chemical properties of globular cluster stars are: 1) deep mixing, involving processes occurring within stellar interiors during the course of their evolution; and 2) chemical pollution from previous stellar generations.

The deep mixing mechanism, which brings freshly processed material to the surface, is expected to operate in evolved low and intermediate mass stars (IMS). Support for this hypothesis comes from the decreasing C abundance during the red giant branch (RGB) ascent (Grundahl et al. 2002). Temperatures in stars below the turnoff are not high enough to synthesise Na and Al, nor do they possess a deep convective layer. Thus the detection of O-Na and Mg-Al anticorrelations in less evolved stars (Gratton et al. 2001; Grundahl et al. 2002; Yong et al. 2003) suggests that these chemical patterns were already present in the gas from which these stars formed, or in gas that accreted onto the surface of cluster stars. The most popular candidates for introducing Na- and Al-rich, O- and Mg-poor gas into the cluster are 4–7 M$_\odot$ intermediate mass stars (IMS) on the asymptotic giant branch (AGB). Cottrell & Da Costa (1981) described one variety of AGB pollution whereby GC stars are born from gas contaminated by AGB ejecta. Another possibility involves the accretion of AGB matter into the atmospheres of existing stars (e.g. D'Antona et al. 1983, Jehin et al. 1998, Parmentier et al. 1999).

We have tested the AGB pollution scenario by calculating the chemical evolution of globular cluster NGC 6752 using a two stage formation scenario similar to the model developed by Parmentier

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et al. (1999). Parmentier et al. investigated primarily the *dynamical* evolution of globular clusters, finding that protoclusters can sustain a series of SNe II explosions without being disrupted. They assumed two distinct evolutionary episodes. Firstly, the birth of stars from a primordial gas cloud leads to a SNe II phase whose expanding shell sweeps up the interstellar medium (ISM) into a dense layer. This triggers the formation of a second generation of stars. In the second phase, intermediate mass stars from the second stellar generation lose their envelopes due to stellar winds. This nuclear-processed material can then be accreted onto the surfaces of lower mass stars.

Thoul et al. (2002) further explored this scenario by calculating the amount of AGB ejecta retained by globular clusters as well as the efficiency with which low mass stars can accrete the intracluster material. They estimate that as much as 95% of the gas in NGC 6752 has been accreted by cluster stars. They arrive at this value by assuming that stars have chaotic motions and spend 20% of their time in the central homogeneous reservoir of gas. It should be noted that their results are quite sensitive to the choice of core radius and stellar velocity, for which they adopted present-day values. Furthermore, they assume that the only method for gas-removal is via tidal sweeping as the cluster crosses the Galactic plane. On the other hand, Smith (1999) proposed that main-sequence stars may generate winds capable of sweeping all the ejecta from globular clusters, provided that the line-of-sight velocity dispersion is less than 22 km/s.

Denissenkov & Herwig (2003) have recently modelled the surface abundance of a single metal-poor 5 $M_\odot$ star and found that it is very difficult to simultaneously deplete O and enhance Na. Furthermore, they found that excess Na is correlated with higher ^{26}Mg *and* ^{25}Mg abundances, whereas Yong et al. (2003) only observed a correlation between Na and ^{26}Mg in NGC 6752. Given the fine-tuning required to deplete O, and the conflict between the predicted surface composition of the heavy Mg isotopes and the data, Denissenkov & Herwig (2003) question the role of hot-bottom burning (HBB) during the thermally-pulsing AGB phase in imposing the anticorrelations. In another recent study, Denissenkov & Weiss (2004) point out that the combination of subsolar [C/Fe] and [O/Fe] and very high [N/Fe] observed in GC subgiants cannot be explained by the operation of HBB in AGB stars. We reach similar conclusions to these authors, but based on a fully self-consistent chemical evolution model of NGC 6752 using yields from 1.25 – 6.5 $M_\odot$ stars with initial compositions determined by the products of population III stars.

We present a globular cluster chemical evolution (GCCE) model that examines in detail whether the impact of AGB stellar winds on the chemical composition of the intracluster medium is consistent with empirical constraints. This model doesn't discriminate between the case where clusters stars form from gas already contaminated by AGB ejecta or the case where existing stars accrete AGB material[1]. The details of the model are described in Section 2. The theoretical predictions are shown in Section 3 and compared with observations. Finally, the relevance of this study to the understanding of globular cluster formation and evolution is discussed in Section 4.

[1] In the latter case, our model gives the composition of the accreted matter only. When the star ascends the giant branch, and experiences the first dredge-up, the (polluted) envelope is mixed with the (original) interior to produce a different surface composition. This is not likely to alter our conclusions, however.

2 THE CHEMICAL EVOLUTION MODEL

The chemical evolution of NGC 6752 was predicted using a two stage formation model. The first stage traced the chemical evolution of initially primordial gas following the formation of population III stars. This stage effectively acted as a prompt initial enrichment, bringing the gas up to a metallicity of [Fe/H] = -1.4 (Gratton et al. 2001 reported a cluster metallicity of [Fe/H] = -1.42, while Yong et al. 2003 found [Fe/H] = -1.62) and imprinting it with the signature of pop III ejecta. During the second stage, globular cluster stars formed from this low-metallicity, α-enhanced gas.

2.1 First stage: Initial enrichment

The conversion of primordial gas into stars was governed by a bimodal initial mass function (IMF) (Nakamura & Umemura 2001) favouring the formation of massive stars. Star formation occurred in a single burst, with newly synthesised elements being returned on timescales prescribed by mass dependent lifetimes (Gusten & Mezger 1982). The set of zero-metallicity yields from Chieffi & Limongi (2002) were used to calculate the enrichment from stars with mass $13 < m/M_\odot < 80$. For more massive stars, yields were given by Umeda & Nomoto (2002), which cover the mass range $150 < m/M_\odot < 270$. Yields for intermediate and low mass stars were from the code described in Karakas & Lattanzio (2003), supplemented with yields for additional isotopes as well as unpublished yields for metallicity Z=0.0001. It should be emphasised that intermediate mass stars played a negligible role in shaping the abundance pattern imposed by the initial enrichment stage, due to the "top-heavy" IMF.

2.2 Second stage: Globular cluster formation and evolution

A second generation of stars was then formed from the [Fe/H] = -1.4 gas enriched by the Population III burst. It has been suggested that expanding shells from the first Type II SNe may trigger further star formation (e.g. Thoul et al. 2002). This model adopted a timescale of 10^7 yr for the second epoch of star formation. A standard Kroupa, Tout, & Gilmore (1993) IMF was adopted, however we assumed that the globular cluster retains the ejecta from stars with $m \leqslant 6.5$ $M_\odot$. Thus, only the yields from intermediate mass stars impact upon the chemical evolution of the intracluster medium during this second stage. No contribution from Type Ia SNe was included in this GCCE model. The observed uniform iron abundance implies that SNe Ia cannot have polluted the cluster during the second formation stage, while their relatively long characteristic timescales precludes them from participating during the first phase of enrichment. We imposed a high efficiency for converting gas into stars, such that at the end of our simulation the chemical composition is a blend of roughly 1 part Pop III enriched gas to 3 parts AGB ejecta. Different assumptions will give different mixtures, but will not alter our main conclusions.

2.3 Chemical yields from AGB stars

A grid of yields in the mass range 1.25 - 6.5 $M_\odot$ was specifically calculated for this investigation by Campbell et al. (2004) using the Mount Stromlo Stellar Structure code (described in Frost & Lattanzio 1996; Karakas & Lattanzio 2003). Table 1 presents the total mass (in solar mass units) of C, N, O, Na, Al and the Mg isotopes released from a star during its lifetime, as a function of initial stellar mass.

Table 1. Intermediate Mass Stellar Yields (in solar masses)[1]

	Initial stellar mass $M_\odot$				
	1.25	2.5	3.5	5.0	6.5
C	8.0×10^{-4}	1.9×10^{-2}	1.6×10^{-2}	9.1×10^{-3}	7.5×10^{-3}
N	4.7×10^{-5}	2.6×10^{-3}	3.6×10^{-4}	6.7×10^{-2}	4.0×10^{-2}
O	6.8×10^{-4}	2.1×10^{-3}	3.0×10^{-3}	2.1×10^{-3}	1.4×10^{-3}
^{24}Mg	3.4×10^{-5}	1.0×10^{-4}	1.5×10^{-4}	8.6×10^{-5}	1.2×10^{-5}
^{25}Mg	5.0×10^{-8}	1.6×10^{-5}	3.5×10^{-5}	5.5×10^{-4}	4.4×10^{-4}
^{26}Mg	4.0×10^{-8}	1.2×10^{-5}	6.1×10^{-5}	1.4×10^{-3}	6.1×10^{-4}
Na	4.3×10^{-7}	2.0×10^{-5}	2.4×10^{-6}	8.7×10^{-4}	7.8×10^{-5}
Al	3.0×10^{-7}	1.1×10^{-6}	3.1×10^{-6}	6.3×10^{-5}	5.8×10^{-5}

[1] additional AGB models to appear in Campbell et al. 2004

The initial elemental abundances of these detailed stellar models were imposed by the chemical composition of the gas enriched by the Pop III burst. In this way, the chemical evolution model is fully consistent with the adopted nucleosynthetic prescriptions.

In order to estimate the sensitivity of our results to the prescriptions used in the stellar evolution calculations, additional models were run using an alternative: 1) set of reaction rates and 2) AGB mass-loss prescription – two of the key factors influencing the final yields in stellar evolution models. The fiducial set of AGB yields was calculated using a Reimers (1975) mass-loss law on the RGB and the Vassiliadis & Wood (1993) mass-loss law during AGB evolution, while most of the reaction rates came from the Reaclib Data Tables (Thielemann, Arnould & Truran 1991). The reader is referred to Karakas & Lattanzio (2003) for greater details of the stellar models. For comparison with the fiducial set of yields, stellar models were run for two representative masses, 2.5 and 5.0 $M_\odot$, with the following modifications: 1) "standard" reaction rates[2] were replaced with NACRE (Angulo et al. 1999) values for the Ne-Na, Mg-Al and ^{22}Ne+α-capture chains; and 2) the Vassiliadis & Wood (1993) AGB mass-loss law was replaced with the Reimers (1975) law (η_{AGB} = 3.5). For almost all species considered in this paper, the final yields predicted using the two sets of reaction rates agree to within 0.1 dex. The yields are more sensitive to the change in mass-loss law, as is discussed in Section 3. The efficiency of dredge-up in AGB stars is another crucial factor influencing the chemical yields. While sensitivity to dredge-up was not explicitly investigated in the present study, Karakas & Lattanzio (2003) tested the effects of reducing the third-dredge-up parameter to about a third its standard value for the final thermal pulses in the most massive AGB stars. They found that the yields of ^{23}Na, C, N and O changed by only a few percent and ^{25}Mg, ^{26}Mg and ^{27}Al yields changed by less than 0.15 dex (see their Table 4). A more detailed analysis of the dependence on dredge-up will be published elsewhere.

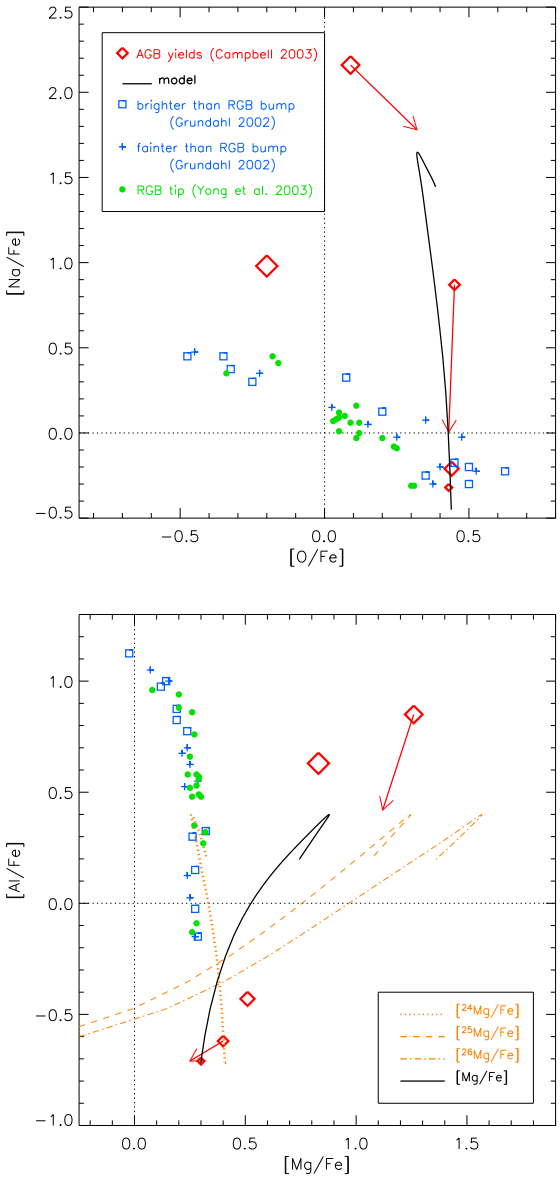

Figure 1. Predicted trend of [Na/Fe] versus [O/Fe] (*a*)) and [Al/Fe] versus [Mg/Fe] (*b*)) (*thick curve*) shown against observational data from Grundahl et al. 2002 (*squares and pluses*) and Yong et al. 2003 (*circles*). Data from Yong et al. were shifted onto the Grundahl et al. scale. Diamonds correspond to the 1.25, 2.5, 3.5, 5.0, and 6.5 $M_\odot$ stellar models of Campbell et al. 2004, where the size of the symbol indicates the stellar mass. Arrows indicate the effects of changing the mass-loss law for 2.5 and 5.0 $M_\odot$ stars (see text for details). In the lower panel, the evolution of [^{24}Mg/Fe], [^{25}Mg/Fe], and [^{26}Mg/Fe] are shown by dotted, dashed, and dot-dashed lines, respectively.

3 RESULTS

Figure 1 compares the observed Na-O (*upper panel*) and Al-Mg (*lower panel*) anticorrelations in NGC 6752 with model predictions. Data from Grundahl et al. (2002) and Yong et al. (2003) show Na-O and Al-Mg anticorrelations in stars that are both brighter and fainter than the RGB bump. We note that Gratton et al. (2001) observed similar general abundance trends, but owing to larger scatter we have omitted their data from this figure. There are ~ 1 dex spreads measured in O, Na, and Al relative to Fe and a 0.3 dex spread in Mg. The observed anticorrelation between [Na/Fe] and [O/Fe] is poorly matched by the theoretically predicted chemical evolution of the NGC 6752 intracluster medium. The enrichment

[2] While most reaction rates in the fiducial AGB models come from the Reaclib library (Thielemann, Arnould & Truran 1991), many of the important rates for producing Mg and Al isotopes have been updated. These include: ^{24}Mg(p,γ)^{25}Al (Powell et al. 1999); ^{25}Mg(p,γ)^{26}Al (Iliadis et al. 1996); ^{26}Mg(p,γ)^{27}Al (Iliadis et al. 1990); ^{22}Ne(α, n)^{25}Mg and ^{22}Ne(α, γ)^{26}Mg (Kaeppeler et al. 1994).

from Pop III stars brings the gas initially to the lower right-hand part of the curve (i.e. [Na/Fe] ~ -0.45 and [O/Fe] $\sim +0.45$). The composition of the intracluster gas then progresses along the curve toward increasing Na, as the material processed within IMS is released through stellar winds. The shape of the curve can be understood by examining the predicted yields from AGB stars, shown in both panels of Figure 1 by five diamonds whose size indicates the corresponding stellar mass (i.e. 1.25, 2.5, 3.5, 5.0, or 6.5 $M_\odot$). The 6.5 $M_\odot$ model (*largest diamond*) is the first star to evolve off the main-sequence and release its processed material into the cluster environment. Consequently, the theoretical curve (*solid line*) initially begins to move from the O-rich, Na-poor region of the diagram toward the 6.5 $M_\odot$ diamond. Over time, the products of progressively lower mass stars influence the shape of the curve, bearing in mind that low mass stars greatly outnumber higher mass stars due to the power law IMF.

Only the most massive (6.5 $M_\odot$) AGB model is capable of significantly depleting O on a scale approaching the 1 dex spread in observations. However, given that the reduction in [O/Fe] for the 6.5 $M_\odot$ star is still only ~ -0.6 dex, even a contrived situation whereby only 6 - 7 $M_\odot$ stars pollute the intracluster medium leaves the very subsolar [O/Fe] stars unexplained. Moreover, not enough mass is ejected by 6 - 7 $M_\odot$ stars to form the number of low-O stars observed.

The AGB models have no difficulty generating Na. Matter ejected by the 5.0 $M_\odot$ star has [Na/Fe] ~ 2.2 – almost 500 times higher than the initial Na abundance – yet the corresponding O depletion is a mere ~ 0.3 dex. The operation of hot-bottom burning in more massive IMS is a major production site for Na (as well as Al and Mg isotopes), and Na is ultimately overproduced by this GCCE model. Since stars with $m > 4$ $M_\odot$ are the chief Na production site, the predicted Na/Fe could be reduced by imposing a more severe upper mass limit for retaining stellar ejecta. 6.5 $M_\odot$ was taken as the upper mass limit in this model, however, this value depends on many uncertain properties such as the concentration of mass within the globular cluster and stellar wind strength and mass loss. The predicted Na/Fe could also be reduced if there were increased dilution of the Na-rich AGB ejecta by the Na-poor Pop III material.

The problem here is that the sodium produced is *primary*. Helium burning has produced C which has been dredged into the envelope. The H shell (and HBB) process this into primary N which then captures two alphas during the thermal pulse to produce ^{22}Ne. Some of this Ne is dredged to the surface where the H shell (and HBB) turn it into the excess Na seen in Figure 1. The observations demand some Na, but not the huge amounts seen in the models, and this is due to the origin of the Na being the C produced by helium burning.

Arrows in both panels of Figure 1 indicate the effects of changing the mass-loss formalism for the 2.5 and 5.0 $M_\odot$ stellar models. Replacing the "standard" Vassiliadis & Wood (1993) mass-loss law with Reimers (1975) prescription, as described in Section 2.3, leads to decreases in [Na/Fe] of roughly -0.9 and -0.4 dex for the 2.5 and 5.0 $M_\odot$ models, respectively. Oxygen is almost unchanged for 2.5 $M_\odot$ while at 5.0 $M_\odot$ [O/Fe] is about 0.2 dex higher in the Reimers mass-loss case. Only the shift due to mass-loss is plotted because it dominates over the effect from changing the reaction rates. Sodium yields are significantly higher with the Vassiliadis & Wood (1993) mass-loss law, owing to the increased number of third dredge-up episodes that progressively increase the Na abundance at the surface, and to the fact that much of the convective envelope is lost during the final few thermal pulses, when the surface abundance of Na is at its highest. Because the rate of mass-loss proceeds more steadily under the Reimers (1975) law, more material is lost earlier on in the AGB phase, prior to the high envelope abundance of Na. While the adoption of Reimers (1975) mass-loss helps remedy the problem of Na overproduction, it only worsens the oxygen discrepancy. This is because depletion of ^{16}O in the stellar envelope is due to HBB, which operates for a shorter time in models with Reimers mass-loss (due to the faster initial mass-loss rate as compared to Vassiliadis & Wood (1993)). In addition, ^{16}O is only significantly depleted in models with $m \gtrsim 5$ $M_\odot$, since these models exhibit (high temperature) HBB.

We stress that a disagreement between the GCCE model and the data would exist regardless of the precise shape of the IMF. Indeed, inspection of the individual yields of AGB stars of various masses reveals that no choice of IMF would reproduce the observations.

The lower panel of Figure 1 shows that this GCCE model predicts about a 1 dex spread in [Al/Fe]. The predicted spread is consistent with the star-to-star variation, but the absolute values are ~ 0.6 dex lower than observed. In stark contrast to the measured Al-Mg anticorrelation, we predict that the total Mg abundance *increases* with increasing Al. This discrepancy would not be resolved by any choice of IMF, since none of the yields of individual stars are depleted in total Mg. Once again, the shape of the theoretical curve reflects the yields from different mass AGB stars (*diamonds*) with different lifetimes and the arrows reflect the effect of changing the mass-loss law. It is evident that both mass-loss cases lead to a discrepancy with the data. The Pop III burst leaves a high-Mg, low-Al chemical signature on the gas from which the intermediate and low mass stars begin to form. The intracluster gas is then enriched in both Mg and Al, which are produced by the AGB stars and expelled through stellar winds. The increase in [Mg/Fe] is entirely due to the enhanced abundance of the heaviest magnesium isotopes, ^{25}Mg and ^{26}Mg, which are produced primarily in the He-burning shell of intermediate-mass AGB stars (Karakas & Lattanzio 2003). The dramatic increase in the heavier Mg isotopes is revealed by the dashed and dot-dashed lines showing the behaviour of [^{25}Mg/Fe] and [^{26}Mg/Fe], respectively. Isolating [^{24}Mg/Fe] (*dotted line*), we recover an anticorrelation resembling the data, albeit offset to lower [Al/Fe] values. Hot-bottom burning in the more massive AGB stars is responsible for this slight depletion of ^{24}Mg, which is converted into ^{25}Mg. However, this only occurs for $m \gtrsim 5$ $M_\odot$, where temperatures in the H-shell exceed 90 million K. It should be noted that the uncertainty in the ^{26}Mg(p,γ)^{27}Al reaction rate permits significantly more ^{27}Al being produced at the expense of ^{26}Mg (Arnould, Goriely, & Jorissen 1999) than in the present models.

Once again, the problem is the products of helium burning. The primary ^{22}Ne mentioned earlier also suffers alpha captures to produce the heavy Mg isotopes via ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg Thus the Mg seen in these AGB stars is again primary, and due to Helium burning. The anti-correlation seen in many globular clusters between Mg and Al is totally swamped by the production of Mg in the helium burning region. Thus our models predict an *increase* in total Mg whereas the data show a *decrease*.

Isotopic ratios have the potential to offer more insight into the source of anomalous chemical patterns than elemental abundances alone. Unfortunately, the important reaction rates for the production of Mg isotopes are beset by uncertainties. In particular, the yield of ^{26}Mg/^{25}Mg from AGB stars is sensitive to the ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg rates, neither of which are tightly constrained (see Figure 12 from Arnould, Goriely, & Jorissen 1999). In Figure 2 we show the variation in Mg isotopic ratios as a function of O, Na, Mg, and Al abundance. The circles rep-

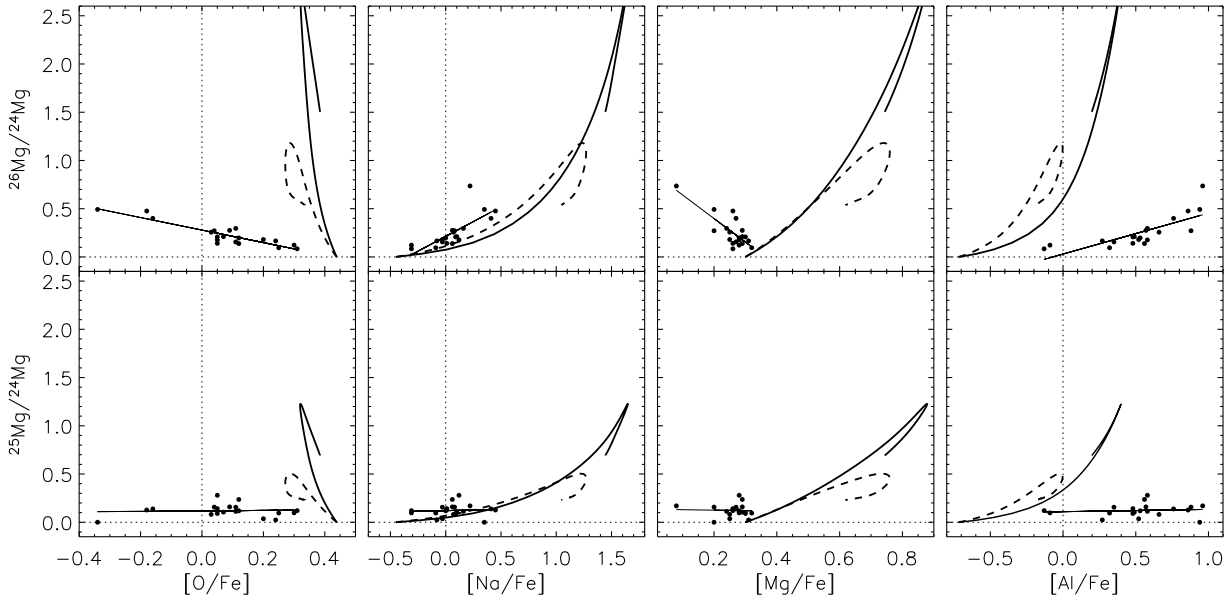

Figure 2. The trend of Mg isotopic ratios with O, Na, Mg, and Al abundance predicted by the NGC 6752 model presented in this paper. The thick solid lines show predictions for ^{25}Mg/^{24}Mg (*top panels*) and ^{26}Mg/^{24}Mg (*bottom panels*). Dashed lines show predictions from the Reimers (1975) AGB mass-loss model, as described in the text. Circles correspond to data from Yong et al. 2003 showing positive correlations between ^{26}Mg/^{24}Mg and [Na,Al/Fe]; anticorrelations between ^{26}Mg/^{24}Mg and [O,Mg/Fe]; and no correlation for ^{25}Mg/^{24}Mg. The lines of best fit to the data are represented by thin lines.

resent measurements of stars at the tip of the red giant branch in NGC 6752 by Yong et al. (2003). The thick solid lines are predictions from our standard model with Vassiliadis & Wood (1993) mass-loss. Predictions from the Reimers (1975) AGB mass-loss model are indicated by dashed lines (where we interpolated and extrapolated the uncertainty calculated for the 2.5 and 5 $M_{\odot}$ stars to other masses). The behaviour of ^{26}Mg/^{24}Mg and ^{25}Mg/^{24}Mg is shown in the upper and lower series of panels, respectively. Yong et al. (2003) revealed clear anticorrelations between ^{26}Mg/^{24}Mg and [O,Mg/Fe] and positive correlations between ^{26}Mg/^{24}Mg and [Na,Al/Fe]. Conversely, there is no evidence that ^{25}Mg/^{24}Mg varies with the abundance of these four elements. Theoretical predictions based on current theories of AGB nucleosynthesis deviate markedly from the observations in a number of important ways: 1) Al-rich and O-poor stars are expected to have much higher (^{25}Mg + ^{26}Mg)/^{24}Mg ratios than is observed, 2) the ^{25}Mg abundance is tightly linked to ^{26}Mg abundance in the models, counter to observations, and 3) the predicted trend of ^{25,26}Mg/^{24}Mg with total Mg abundance (i.e. [Mg/Fe]) moves in the opposite direction to the data, due to the primary production of Mg in these AGB stars. Regarding the first point, we stress that the overproduction of ^{25,26}Mg by our GCCE model is not disastrous for the AGB self-pollution scenario. Lower values of (^{25}Mg + ^{26}Mg)/^{24}Mg could be obtained by diluting the AGB ejecta with more of the initial gas. Moreover, the dashed lines demonstrate that a factor of ~ 2 reduction in the AGB yield of (^{25}Mg + ^{26}Mg)/^{24}Mg can be attained by adopting a "steadier" rate of of AGB mass-loss, such as the Reimers (1975) prescription described in Section 2.3. However, points 2 and 3, listed above, represent more serious problems for the AGB self-pollution picture, and are robust to the variations in stellar inputs considered in this study.

Figure 3 compares the predicted trend of [N/Fe] versus [C/Fe] from the AGB pollution model (*solid line*) against observations of AGB stars in NGC 6752 from Smith & Norris (1993) (*crosses*).

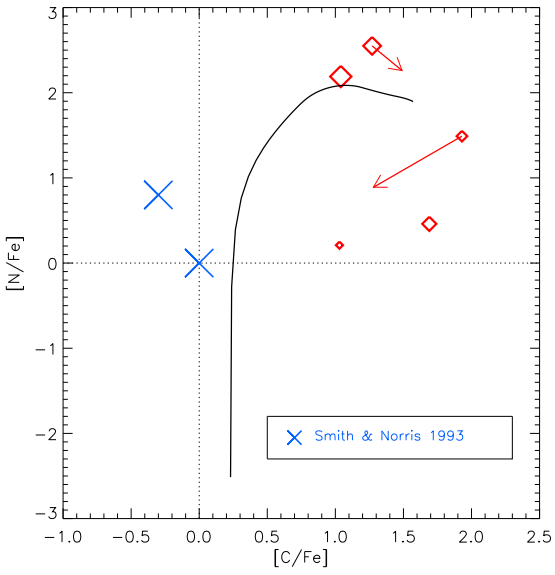

Figure 3. Predicted evolution of [N/Fe] with [C/Fe] (*solid line*). Symbols have the same meaning as in Figure 1 except that crosses denote data from Smith & Norris 1993.

Diamonds correspond to yields from the AGB models for five initial masses from 1.25 to 6.5 $M_{\odot}$, and arrows reflect the effect of changing the mass-loss law. Red giants in NGC 6752 have been found to exhibit bimodal C and N abundances with one group having roughly solar [C/Fe] and [N/Fe], and the other group being N-rich and C-poor (e.g. da Costa & Cottrell 1980; Norris et al. 1981; Smith & Norris 1993). The empirical data points to an anticorrelation between C and N that has previously been explained in terms

of the operation of a deep mixing mechanism in evolved stars. The dependence of the molecular CN-band strength on stellar luminosity (e.g. Suntzeff & Smith 1991) is readily understood as a result of increased mixing of N-rich, C-poor material from within the stellar interior to the surface, as a function of evolutionary stage. More recently, however, Grundahl et al. (2002) found an anticorrelation between [C/Fe] and [N/Fe] in NGC 6752 stars that is independent of luminosity. Cannon et al. (1998) found a similar CN bimodality and anticorrelation in 47 Tuc from a sample of stars that included not just giants, but also unevolved main-sequence stars whose shallow convective layers preclude dredge-up of CNO-cycled material. The presence of the same CN trend in both dwarfs and giants led Cannon et al. (1998) to conclude that deep mixing was not singularly responsible for CN abundance anomalies in 47 Tuc. It seems likely that the CN patterns in NGC 6752 stars arise from a combination of deep mixing and some form of external pollution.

Figure 3 casts doubt on AGB stars being a major source of external pollution. All the AGB models from $1.25 - 6.5$ $M_{\odot}$ expel material that is enhanced in both N *and* C. From Figure 3 it is clear that main-sequence stars severely polluted by AGB material are expected to also exhibit heightened C and N abundances. The positive correlation between C and N in the intracluster gas predicted by our GCCE model fails to match the empirical trend, however, we note that our calculations only reflect the chemical evolution of the intracluster medium. The abundance pattern of the gas at a particular time corresponds to the initial composition of stars born at that time, whereas the observed abundance of elements like CNO in evolved red giants are likely to differ from their starting abundances due to internal synthesis and mixing.

Figure 4 reveals an almost order of magnitude rise in [C + N + O/Fe] in the intracluster gas within 1 Gyr of formation. A slight drop in the O abundance is more than compensated for by a dramatic increase in C and N. This robust prediction is based on intermediate mass stellar nucleosynthesis and poses further difficulties for the AGB pollution scenario as an explanation for globular cluster abundance anomalies, since C + N + O is found to be approximately constant in many GCs (Ivans et al. 1999). AGB stars have been proposed in the literature as promising candidates for producing the observed GC abundance anomalies because they exhibit the required hot H burning via hot-bottom burning. However, because these stars also dredge-up the products of He-burning, C + N + O is not conserved in the models, in conflict with the data.

We note that in order to achieve an order of magnitude increase in the intracluster abundance of Al via the AGB pollution scenario, our models simultaneously predict an intracluster medium helium mass fraction, Y, approaching 0.3. This represents a ~ 0.05 increase in Y over the primordial value. D'Antona et al. (2002) have found that the effects on stellar evolution due to this level of He enrichment would be difficult to measure observationally but could lead to extended blue tails in the horizontal branch morphology.

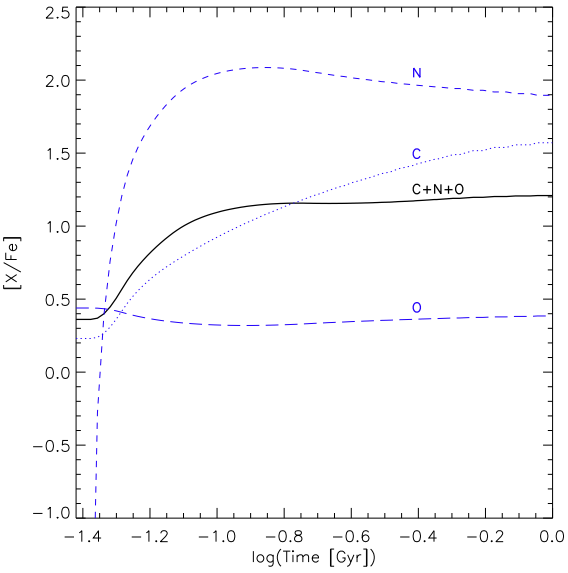

Figure 4. Temporal evolution of [C/Fe] (*dotted line*), [N/Fe] (*short dashed line*), [O/Fe] (*long dashed line*), and [C+N+O/Fe] (*solid line*). In contrast to observations in NGC 6752 and other globular clusters, C+N+O abundance is predicted to vary by an order of magnitude if AGB stars are responsible for the Na and Al enhancement.

4 CONCLUSIONS

The presence of variations in C, N, O, Mg, Na, and Al in globular cluster stars yet to ascend the red giant branch provides compelling evidence for these chemical patterns already being in place in the gas from which cluster stars formed, or in gas that later polluted their atmospheres. Otherwise, one would expect to see chemical homogeneity in stars below a certain luminosity, unless our understanding of deep mixing is seriously flawed. We have constructed a self-consistent model of the chemical evolution of the intracluster gas, that included custom-made detailed stellar models, to test whether the observed inhomogeneities may be caused by contamination from material processed by intermediate mass stars during their AGB phase. This model is compatible with either a scenario in which there is coeval and stochastic sweeping of the intermediate mass stellar ejecta by existing lower mass stars, or one in which new stars form from AGB polluted material. In the latter case, there would be a small age spread with Na-rich stars being a few hundred million years younger than Na-poor stars.

We find that, regardless of either the mechanism for polluting cluster stars with AGB material or the level of dilution of Pop III material by AGB ejecta, intermediate mass stars are unlikely to be responsible for most of the abundance anomalies. While metal-poor AGB models generate large quantities of Na and Al that may account for the observed spread in these elements in NGC 6752, the AGB pollution scenario encounters a number of serious problems: 1) O is not depleted within AGB stars to the extent required by observations, 2) Mg is *produced* when it should be *destroyed*, 3) C+ N + O does not remain constant in AGB processed material, and 4) ^{25}Mg is correlated with ^{26}Mg in the modelled AGB ejecta, conflicting with the Yong et al. (2003) observations.

Note that all of these problems stem from the addition of helium burning products into the AGB star ejecta. Perhaps a generation of AGB stars which experience HBB but almost no dredge-up would fit the data better!

The model presented in this paper could be generalised for application to other globular clusters by varying three main parameters: the initial metallicity; the upper mass limit beyond which stellar winds are too energetic for the cluster to retain the ejecta (this depends on the mass concentration and gravitational potential); and the efficiency and duration of star formation.

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